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# AC Bias Characterization of Low Noise Bolometers for SAFARI Using an Open-Loop Frequency Domain SQUID-based Multiplexer Operating Between 1 and 5 MHz

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**Abstract** SRON is developing the Frequency Domain Multiplexing (FDM) read-out and the ultra low NEP TES bolometers array for the infra-red spectrometer SAFARI on board of the Japanese space mission SPICA. The FDM prototype of the instrument requires critical and complex optimizations. For single pixel characterization under AC bias we are developing a simple FDM system working in the frequency range from 1 to 5 MHz, based on the open loop read-out of a linearized two-stage SQUID amplifier and high  $Q$  lithographic  $LC$  resonators. We describe the details of the experimental set-up required to achieve low power loading ( $<1$  fW) and low noise ( $NEP \sim 10^{-19}$  W/ $\sqrt{\text{Hz}}$ ) in the TES bolometers. We conclude the paper by comparing the performance of a  $4 \times 10^{-19}$  W/ $\sqrt{\text{Hz}}$  TES bolometer measured under DC and AC bias.

**Keywords** FDM · Infra-red detector · SQUID · Bolometer · TES · LC resonator

## 1 Introduction

In this paper we describe a Frequency Domain Multiplexer meant for laboratory tests and designed to increase the experimental throughput in the characterization of TES bolometer array under AC bias. To simultaneously measure a large number of pixels a baseband feedback scheme [1] is required. However, to perform a single pixel characterization, each AC channel can be read-out sequentially in time. In this way

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the SQUID amplifier dynamic range is less critical and the instrument and its electronics can be greatly simplified.

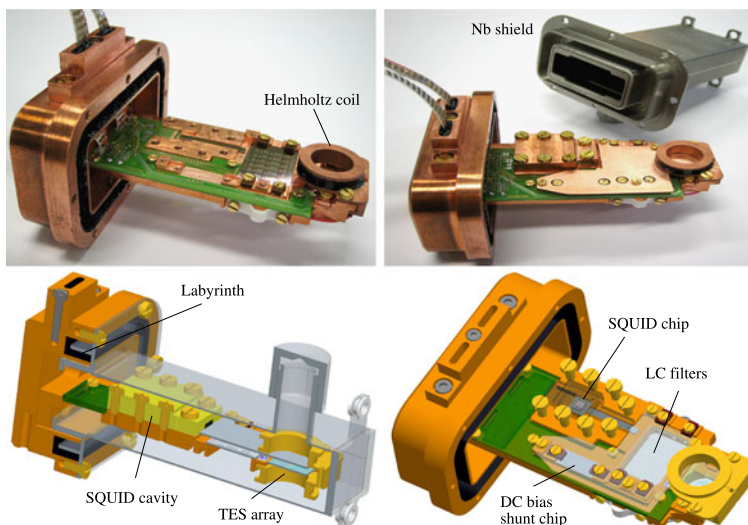
We took into account the following requirements while designing the multiplexer. It should allow the read-out of tenths of pixels biased at AC voltage in the frequency range from 1 to 5 MHz. Several pixels on the array should be biased at DC voltage to allow direct comparison with the AC biased ones under identical experimental conditions. It should have easy-to-use read-out electronics. The multiplexers will be used both with ultra-low noise equivalent power (NEP) TES bolometers and with high energy resolving power x-ray microcalorimeters. The former require very low background power levels, which is achieved by means of light blocking filters in the signal loom feedthroughs and a light-tight assembly. Special care has been taken to design the magnetic shielding and to improve the uniformity of the applied magnetic field across the array. In the second part of the paper we compare the performance of a  $4 \times 10^{-19} \text{ W}/\sqrt{\text{Hz}}$  TES bolometer measured under DC and AC bias at a frequency of 1.3 MHz. In the AC bias case the bolometer is measured with a multiplexer based on discrete  $LC$  resonators and other circuit components used in our standard DC bias set-up.

## 2 Overview of the Open-Loop Frequency Domain Multiplexer

The mechanical assembly of the Open Loop Frequency Domain Multiplexer (OL-FDM) consists of a low magnetic impurity copper bracket fitted into a Nb can. The matching of the Nb can with the bracket lid is not vacuum-tight and was designed such that it forms a labyrinth, which is filled with carbon loaded epoxy on the copper lid side. In this configuration the Nb can provides both the required magnetic and stray light shielding. A photograph and a CAD image of the OL-FDM set up is shown in Fig. 1. The electrical connections from the cold stage of the cooler to the SQUID and TES bias circuit elements are achieved by means of superconducting looms fed through a narrow 10 mm long channel filled with carbon loaded epoxy. The circuit PCB board is designed to host 2 DC and 18 AC bias channels. The latter is achieved by using the lithographic high- $Q$   $LC$  resonators arrays developed at SRON [2]. The nominal inductance of the coil used in each filter is  $L = 400 \text{ nH}$ , while the capacitances  $C$  are designed such that the frequencies  $f_0 = \frac{1}{2\pi\sqrt{LC}}$  are spread at a constant interval in the range from 1 to 5 MHz.

The SQUID amplifier chip is placed in a radiation shielding cavity whose inner side is coated with a 2 mm thick radiation absorber made from carbon loaded epoxy with mixed SiC grains of size from 100  $\mu\text{m}$  to 1 mm [3, 4]. This precaution was taken to minimize possible loading of the bolometers due to Josephson radiation, typically in the range of 4–8 GHz, emitted by the SQUID junctions. The electrical connection from the SQUID chip to the  $LC$  filters is done by means of Nb strip lines on a 20 mm long interconnection chip. These lines act as a low-pass filter with a calculated roll-off around 500 MHz.

The perpendicular magnetic field of the TES array is controlled by means of a superconducting Helmholtz coil, which generates an uniform field over the whole pixels array.



**Fig. 1** (Color online) Photograph and CAD models of the Open Loop Frequency Multiplexer prototype

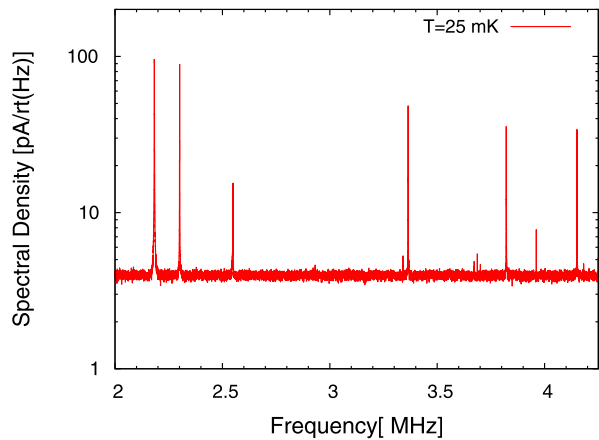
### 3 Performance of the Linearized SQUID Amplifier

A crucial component of the multiplexer described above is the SQUID amplifier. We use a low noise two-stage PTB SQUID current sensor with on chip linearization, low input inductance ( $L < 3$  nH) and low power dissipation ( $P < 20$  nW) [5]. The SQUID with on chip linearization [6] has a larger dynamic range with respect to the standard voltage sampled SQUID and guarantees a linear amplification of the AC biased bolometers signal. We operate the SQUID in open loop. The output signal is amplified by a 20 MHz bandwidth, low input voltage noise, commercial electronics (Magnicon B.V). To test the performance of the SQUID amplifier under loaded condition we coupled 6 high parallel  $LC$  lithographic resonators to its input coil. At temperature  $T = 25$  mK we measured a SQUID input current noise of  $4 \text{ pA}/\sqrt{\text{Hz}}$  (with  $1/M_{in} = 19.6 \text{ } \mu\text{A}/\Phi_0$ ) over the whole interesting frequency range from 1 to 5 MHz (Fig. 2). All the six resonators had  $Q$  factors larger than  $10^4$ . The SQUID operates in a linear regime for input current lower than  $12 \text{ } \mu\text{A}$ .

### 4 Characterization of a Low Noise Bolometer at 1.3 MHz in a Pilot Set-up

The experiment described in the following section was carried on in a pilot set-up, described below, which is different from the one previously presented. The detector used in the experiment is a low G TES bolometers with a transition temperature of  $T_C = 78.5$  mK, a normal state resistance of  $R_N = 101$  m $\Omega$  and a calculated NEP of  $2 \times 10^{-19} \text{ W}/\sqrt{\text{Hz}}$ . The sensor was previously characterized under DC bias and showed a power plateau of 3.7 fW and a dark NEP of  $4.2 \times 10^{-19} \text{ W}/\sqrt{\text{Hz}}$  [7]. We tested the bolometer under AC bias at a frequency of 1.3 MHz in a three pixels FDM configuration, where two similar pixels were connected to the other LC resonators

**Fig. 2** (Color online) Squid current noise with 6 coupled high- $Q$  lithographic resonators. The  $Q$ -factor of the resonators ranges from 10000 to 20000



tuned at 2.3 and 4.2 MHz respectively. The latter pixels were not biased. The TES array carrying the three pixels is mounted into the light-tight box used in the DC bias experiment [7] and the connections to the resonators were done by means of relatively long twisted pairs.

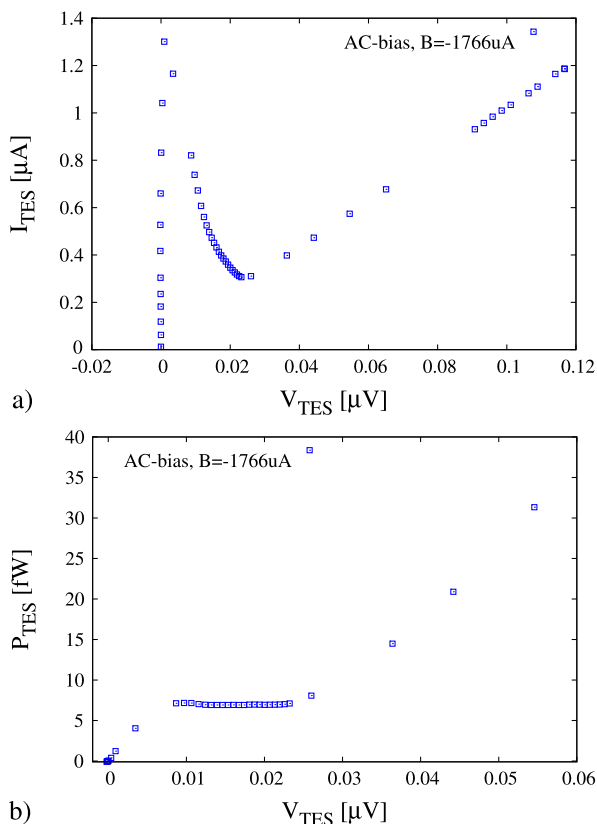
The three LC resonators consist of hybrid filters made of lithographic Nb-film coils and commercial high- $Q$  NP0 SMD capacitors with  $C_1 = 22$  nF,  $C_2 = 4.4$  nF,  $C_3 = 2.2$  nF respectively. For the read-out of the TES current we use a NIST SQUID arrays consisting of a series of 100 dc-SQUID with input-feedback coil turns ratio of 3:1, and input inductance  $L_{in} = 70$  nH. The input current noise is  $\sim 3$  pA/ $\sqrt{\text{Hz}}$  at  $T < 1$  K. The SQUID amplifier is operated in open loop mode using commercial Magnicon electronics. The resonant frequency of the circuit is defined by the capacitors  $C$  and the total inductance  $L_{tot} = L_{in} + L + L_{stray}$ . From the measured resonant frequency and the filter capacitance value reported above we get  $L_{tot} = 0.64$   $\mu\text{H}$ .

In Fig. 3 we show the current-to-voltage and the power-to-voltage characteristics of the TES bolometer under test. We observe a power plateau at 7 fW at a bath temperature  $T_{bath} = 30$  mK and when applying a magnetic field in order to cancel any residual fields perpendicular to the TES. A lower power plateau of 3.7 fW was observed with the same pixel in the measurements performed at DC bias voltage under identical condition, but in a different cooler [9]. The AC bias configuration performs even better than the DC bias case in terms of power loading into the detector probably due to a better EMI filtering of the input bias lines.

We further characterized the detector under AC bias by measuring the noise and the complex impedance as a function of the TES resistance. A simple two body model [8] is used to fit the impedance data and to derive the parameters, like  $\beta$ , loop gain  $L_o = P_o \alpha / GT$  and time constant  $\tau_o = C/G$ , needed to estimate the detector responsivity. A distributed model would provide a more accurate estimation of those parameters [9]. In Fig. 4 we plot the TES current noise and the dark NEP for several TES resistances.

At bias points high in the transition ( $R/R_N > 60\%$ ) an  $\text{NEP} = (5.2 \pm 0.6) \times 10^{-19}$  W/ $\sqrt{\text{Hz}}$  is observed. The uncertainty in the NEP estimation is due to calibration errors. We observed a deterioration of the dark NEP at low TES resistances due

**Fig. 3** (Color online) Current-to-voltage (a) and the power-to-voltage (b) characteristics of the TES bolometer measured at an AC bias frequency of 1.3 MHz



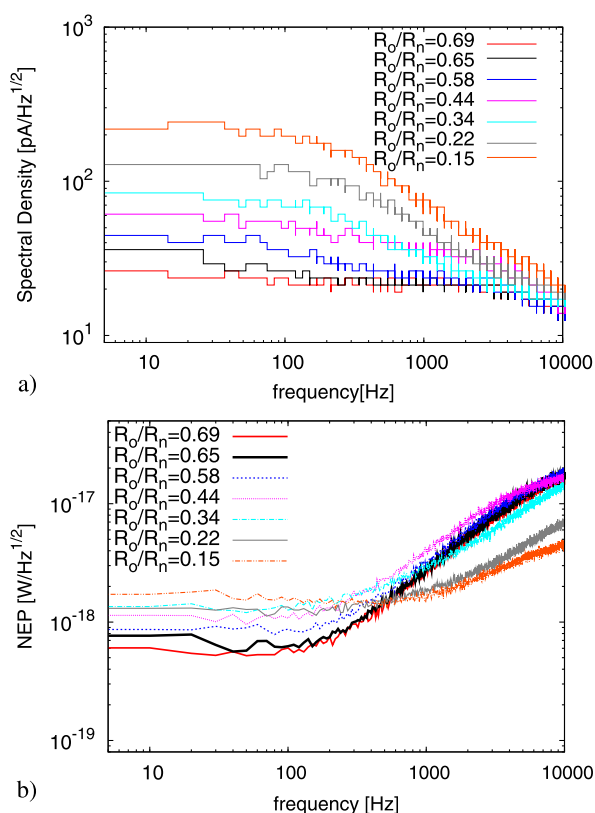
to excess noise at low frequency. The detector noise can be modeled using the parameter obtained from the impedance data. We can fully explain the measured noise at any bias point in the transition assuming a voltage noise  $\sqrt{S_V} \sim 2 \text{ pV}/\sqrt{\text{Hz}}$  in series with the TES. The current noise generated by the voltage source has the same signature of a thermal noise from the shunt resistance used in the DC bias case. This is clearly seen in Fig. 5, where the different noise contributions, including the shunt-like noise, are overplotted to the measured noise spectrum.

From the quality factor  $Q$  of the resonance measured with the TES superconducting we infer a total resistance of the read-out circuit of  $r = \frac{1}{\omega_o C Q} = 14.9 \pm 0.3 \text{ m}\Omega$ , where  $\omega_o = 2\pi \times 1.33 \text{ MHz}$ ,  $C = 22 \text{ nF}$  and  $Q = 346 \pm 6$ . Such a small resistance should be at a thermodynamic temperature of about 4 K to generate the voltage noise level needed to explain the measured TES current noise. The excess noise observed is likely to be due to thermal noise leaking from the channel 2 of the FDM system, whose resonator was not functioning properly and had a poor quality factor.

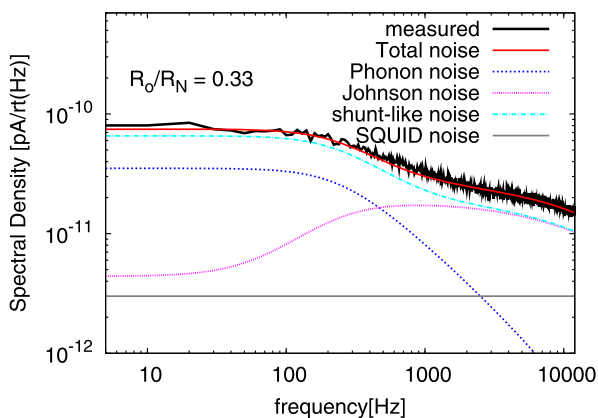
## 5 Conclusion

We are developing a Frequency Domain Multiplexer to increase the experimental throughput in the characterization of TES bolometer array under AC bias.

**Fig. 4** (Color online) TES current noise (a) and dark NEP (b) at different TES resistances for the bolometer measured at an AC bias frequency of 1.3 MHz



**Fig. 5** (Color on line) Measured and modelled current noise for the TES bolometer at a resistance  $R/R_N = 0.33$



The multiplexer is based on the open loop read-out of a linearized two-stage SQUID amplifier and high  $Q$  lithographic LC resonators and is designed to work in the frequency range from 1 to 5 MHz. We describe the details of the experimental set-up required to achieve low power loading ( $<1$  fW) and low noise ( $\text{NEP} \sim 10^{-19} \text{ W}/\sqrt{\text{Hz}}$ ) in the TES bolometers. The first results are expected soon. In a

pilot experiment performed with a multiplexer obtained by adapting our standard DC bias set-up, we measured a dark NEP =  $(5.2 \pm 0.6) \times 10^{-19}$  W/ $\sqrt{\text{Hz}}$  using a low noise TES bolometer previously characterized under DC bias. We observed a deterioration of the dark NEP for low TES resistances due to excess noise at low frequency. The excess noise is consistent with a voltage noise source in series with the TES as large as  $\sqrt{S_V} \sim 2$  pV/ $\sqrt{\text{Hz}}$  likely to be due to thermal noise leaking from another channel of the FDM system.

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